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CALCULATION OF CLOTHING INSULATION AND VAPOUR RESISTANCE

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TNO-report

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SUMMARY

Based on a physical model, in which a human is depicted as a collection of appropriately sized cylinders, clothing insulation and vapour resistance are calculated for standing persons in still air, when the clothing ensemble thickness, total fabric thickness, number of clothing layers, and number of trapped air layers are specified for each cylinder. Specific knowledge of the clothing material is not required, except when coatings of films are involved. The resulting reference values for clothing insulation and vapour resistance are accurate to a standard deviation of .011 m^2K/W and 1.8 mm of air equivalent, respectively, compared to thermal manikin measurements.
The reference values are modified for sitting, walking, and cycling at various rates, and for the combined effect with wind. The formulas are regression equations on a data base of literature. The resulting total insulation and vapour resistance are accurate to .022 m^2K/W and 3.6 mm of air equivalent, respectively.
The physical model, which is available as software, is a challenge to existing methods for the determination of insulation and vapour resistance with respect to simpleness and accuracy.

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Berekening van kledingisolatie en waterdampweerstand

W.A. Lotens en G. Havenith

SAMENVATTING

De isolatie en dampweerstand van kleding kan bepaald worden voor staande mensen in rustige lucht door middel van een fysisch model, waarin een mens opgebouwd is gedacht uit cylinders van toepasselijke afmetingen, als de dikte van het ensemble, de totale dikte van de kledinglagen, en het aantal kleding- en ingesloten luchtlagen per cylinder gegeven worden. Gegevens over het kledingmateriaal zijn niet nodig zolang er geen folies of coatings inzitten. De resulterende referentiewaarden voor isolatie en dampweerstand hebben een standaarddeviatie van .025 m^2K/W, respectievelijk 1.8 mm luchtequivalent, vergeleken met manikinmetingen.
De referentiewaarden worden aangepast voor zitten en voor lopen en fietsen met diverse snelheden, ook voor het gecombineerde effect met wind. De gebruikte formules zijn regressievergelijkingen op een uit de literatuur samengesteld gegevensbestand. De resulterende isolatie en dampweerstand hebben standaarddeviaties van respectievelijk .022 m^2K/W en 3.6 mm lucht equivalent.
Het fysische model, dat als computerprogramma beschikbaar is, heeft mogelijk een betere balans tussen eenvoud en nauwkeurigheid dan andere methoden om isolatie en dampweerstand te bepalen.

1 INTRODUCTION

The determination of the heat insulation and water vapour resistance of a specific clothing ensemble can be done in several ways, with varying accuracy and effort involved. The methods available are briefly characterized as follows:

- Measurement while the clothing is worn by subjects in the actual or simulated environment. This method is laborious and requires sophisticated equipment but gives realistic data. In particular the measurement of vapour resistance shows large variability, which requires a sufficient number of subjects and statistical analysis to get a result.
- Measurement on a thermal manikin. This method has a better reproducibility, but requires an expensive manikin, and the activities are restricted to the mobility of the manikin and the available driving machines. Manikins are usually available in one size only and have none or primitive sweat control.
- Regression by means of tables of previously determined insulation values. The tables are based on manikin measurements (static, no air motion). Separate items in the tables can be combined to an ensemble by means of a regression equation (Seppanen et al., 1972; Sprague and Munson, 1974; Olesen et al., 1982; McCullough et al., 1985) Vapour resistance data are hardly available.
  The accuracy of the method is rather determined by the identification problems of the actual clothing with listed items than by the accuracy of the listed data (McCullough et al., 1985).
- Regression on physical characteristics of the clothing. This method is in fact more accurate than the former. The best results are obtained with regression on covered skin area and thickness of the pieces of clothing, but the easier to determine total covered area and total ensemble weight predict also reasonably well (McCullough et al., 1985). The method gives no vapour resistance data and has been validated for usual ensembles only.

A fifth method deals with the calculation of heat and mass transfer when the geometry of the clothing is known. To this purpose a human is considered as a collection of cylinders, representing body parts. The relevant clothing properties are used to calculate the local insulation and vapour resistance and all parts are integrated to give the values for standing persons in still air. Such models were developed by McCullough et al. (1985), Mecheels and Umbach (1977) and Lotens (1988b) and recently enhanced by McCullough et al. (1989) and Lotens (1989b). This study is focusing on this type of model, with the aim to

get an optimum in the balance between required input data and accuracy. An important extension is the inclusion of formulas to predict the effect of posture, motion, and wind. The model is validated with a data bank, consisting of a number of studies reported in the literature. It will be shown that this method, which requires only a number of observations which are relatively easy to make, is a challenge to the forementioned methods in the trade-off between accuracy and ease of use.

2 DESCRIPTION OF THE MODEL

2.1 Heat resistance of single layers

The insulation of clothing layers is largely proportional to the thickness. The proportionality constant is the specific resistance with a typical value of 24 mK/W, more or less independent of the type of fibre and the fabric construction. Fig. 1 shows data points for a variety of materials. Similar specific resistance was found by Burton and Edholm (1955).

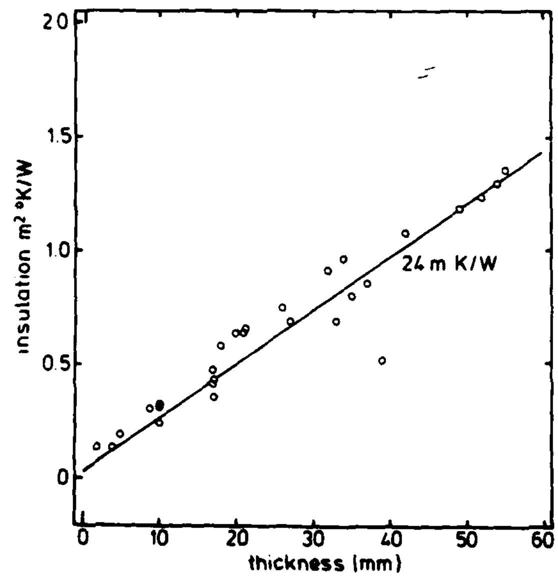


Fig. 1 The relationship between fabric thickness and its insulation.

Since the specific resistance of an air layer of the same width is about 38 mK/W the resistance of fabric is lower than the convective resistance of the air it displaces. The cause for this decrease is the amount of radiative heat transfer the conductance through the fibres. Also for air layers the insulation increases with the width, but in a more complicated way. The radiative heat exchange between the boundary surfaces forms a parallel heat flow, independent from the width of the layer. The heat transfer coefficient is determined by the temperature and emission coefficients of the surfaces:

$$h_r \approx 4 \frac{\epsilon_1 \epsilon_2}{1 - \rho_1 \rho_2} \sigma T^3 \qquad (W/m^2K) \qquad (1)$$

where $\sigma = 5.67\ 10^{-8}$ (Stefan Bolzmann coefficient)

T is the average temperature in K.

ϵ is emission coefficient

ρ is reflection coefficient

According to Cain and Farnworth (1986) for many materials ϵ_1 and ϵ_2 amount to .8 and ρ_1 and ρ_2 to .1, which leads to a typical value for hr of 4 at common clothing temperatures.

The convective part of the heat transfer through an air layer is

$$hc = \lambda/th \qquad (W/m^2K) \qquad (2)$$

where λ = .026 W/m°C (the inverse of the specific heat resistance)

th = width of the layer (m)

The insulation of air layers is thus

$$Ial = \frac{1}{\lambda/th + 4} \qquad (m^2K/W) \qquad (3)$$

For a fairly typical temperature gradient of 5°C the width must be restricted to a value of about 13 mm (Smithsonian tables, 1939; Cain and Farnworth, 1986), since wider gaps tend to show natural convection, which limits hc to a minimal value.

2.2 Vapour resistance of single layers

Due to the strong analogy between conductive and convective heat transfer on one hand and vapour transfer on the other hand, known as the Lewis relation, for air layers the evaporative heat flow can be expressed as a function of hc:

$$\text{Evap} = L\ hc\ \Delta C \qquad (W/m^2) \qquad (4)$$

where L = 2.34 (Km^3/g)

ΔC = vapour concentration gradient (g/m^3)

In this description vapour concentration is used instead of vapour pressure gradient, since this is physically more elegant (Lotens, 1988a) and more simple.

The same expression can be stated in another way, emerging from diffusion physics:

$$\text{Evap} = He\ \frac{\mathbb{D}}{d}\ \Delta C \qquad (W/m^2) \qquad (5)$$

where He = heat of evaporation (2430 J/g)

$\mathbb{D}$ = diffusion coefficient (25 10^{-6} m^2/s)

d = air equivalent (m)

d is a particularly clear way to express vapour resistance, since it represents the actual thickness of an air layer with equivalent resistance for air: d = th. Comparison of eq. 4 and eq. 5 reveals that more generally holds:

$$d = \frac{He\ \mathbb{D}}{L\ hc} = \frac{.026}{hc} \qquad (m) \qquad (6)$$

Lotens (1988a) showed that the factor .026 is indeed the air conductivity λ. d has distinct advantages over other measures for vapour resistance, in terms of clarity, comprehensibility and measurement procedures (Lotens, 1989a).

For layers of fabric d must be larger than the thickness since the diffusion process is not only determined by the thickness of the layer, but by the obstruction due to the fibres as well. The hampering effect is related to the packing of the fibre mass. Whelan et al. (1955) gave an elegant analysis of vapour resistance data, showing that the volume percentage of fibre in the fabric indeed is a dominant factor, regardless of the fibre type. Very dense fabrics are usually thin, while thick fabrics are usually loose. The net result is that d exceeds the thickness of the fabric with 1 to 5 mm (Fig. 2). Due to this regularity it is possible to estimate the air equivalent of fabric layers as

$$d = 1.3\ th + .001 \qquad (m) \qquad (7)$$

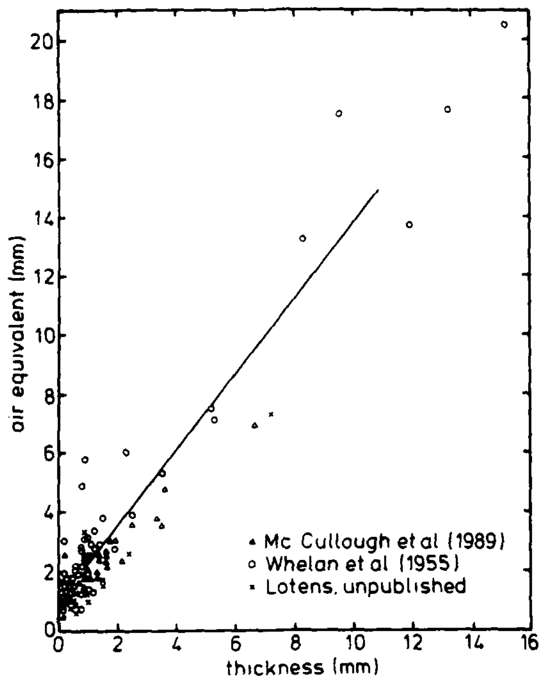


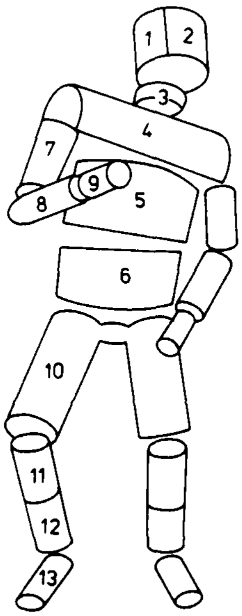
Fig. 2 The relationship between fabric thickness and its water vapour resistance.

Expression 7 is relatively inaccurate for thin fabrics, but its absolute accuracy (standard deviation ≈ 1 mm) is satisfactory for use in ensembles. When fabrics are coated or laminated on film, the air equivalent is unpredictable and should be specified. For reasons of simplicity it is assumed in the calculations that such layers are confined to the outside.

2.3 Geometry

The human body is considered to consist of 13 cylindrical elements, with characteristic curvature and surface area, for the various body parts. The parts are distinguished in such a way that the borderlines tend to coincide with the extension of typical clothing articles on one hand, and that the areas are more or less homogeneous in clothing

fit on the other hand. Fig. 3 shows the articulation. The data regarding curvature and relative surface area are for normally build males. For other body shapes the radii are somewhat different, but this has no large effect on the calculations. The calculations are insensitive to variation in stature.



segment	radius (cm)	area (%)
1	9.5	4
2	9.5	3
3	6.5	1
4	12.0	13
5	16.0	12
6	16.0	10
7	4.5	6
8	4.0	6
9	3.5	5
10	9.0	20
11	6.5	7
12	6.5	6
13	4.5	7

Fig. 3 Articulation of the cylinder model.

Clothing is characterized by four easy to determine parameters per segment: the ensemble thickness (to be determined from the difference in nude and clothed circumference), the total thickness of clothing layers involved, the number of clothing layers, and the number of trapped air layers. The latter can be smaller than the former, in particular for elastic clothing layers. The model assumes all clothing layers to have the average thickness and the same holds for the trapped air layers. The calculation with average thickness of layers gives some loss of accuracy, but the advantage of not needing highly specified input data is judged to be of greater importance.

The various layers in the assembly are put over the bare cylinder.

Since the cylinder radius increases with each layer, the effectivity of the next layer will be slightly decreased due to increased heat dissipating area.

$$I_n = I_{n-1} + \frac{Il_n}{fcl_{n-1}} \tag{8}$$

$$d_n = d_{n-1} + \frac{dl_n}{fcl_{n-1}} \tag{9}$$

$$fcl_n = fcl_{n-1} + \frac{th_n}{r_o} \tag{10}$$

where I_n = insulation up to and including layer n
Il_n = insulation of layer n
fcl_n = surface area ratio of layer n to bare cylinder
th_n = thickness of layer n
r_o = radius bare cylinder

These recurrent expressions are used to don the cylinder successively with clothing and air layers, until after the outmost clothing layer Icl_i, dcl_i and fcl_i are obtained, where i refers to the i-th segment. The various segments are integrated by area weighing of conductances:

$$Icl_{cov} = \sum_i area_i \,/\, \sum_i \frac{area_i}{Icl_i} \tag{11}$$

$$dcl_{cov} = \sum_i area_i \,/\, \Sigma_i \frac{area_i}{dcl_i} \tag{12}$$

$$fcl_{cov} = \sum_i area_i \; fcl_i \tag{13}$$

$$area_{cov} = \sum_i area_i$$

The summation can be carried out over the clothing covered segments only. Since it is common practice to refer for clothing properties to the total body surface area, these values must be transformed to the intrinsic values by means of the relationships

$$\frac{1}{Icl + Ia/fcl} = \frac{area_{cov}}{Icl_{cov} + Ia/fcl_{cov}} + \frac{1 - area_{cov}}{Ia} \qquad (14)$$

$$\frac{1}{dcl + da/fcl} = \frac{area_{cov}}{dcl_{cov} + da/fcl_{cov}} + \frac{1 - area_{cov}}{da} \qquad (15)$$

$$fcl = 1 - area_{cov} + area_{cov} * fcl_{cov}$$

The definition of Icl and dcl thus clearly depends on the insulation (Ia) and vapour resistance (da) of the adjacent air layer and these values should be standardized. According to Havenith et al. (1989a) Ia has the value of ≈ .129 $m^2{}^\circ C/W$ and da of 9.4 mm for standing persons in quiet air.

It should also be noted that the integration over segments implicitly assumes that the skin temperature is uniform over the skin. In the cold this is usually not true. As Lotens (1989b) pointed out, the values of Ia and da, the partial coverage of the body, non uniform insulation and non-uniform skin temperature make the use of Icl and dcl ambiguous.

The total insulation and water vapour resistance are obtained by the usual formulas

$$It = Icl + Ia/fcl \qquad (16)$$

$$dt = dcl + da/fcl \qquad (17)$$

2.4 The effect of activity and wind

The insulation and vapour resistance values for standing persons in quiet air can be used to predict similar values for various activities and air motion. The studies of Havenith et al. (1989a,b) and Lotens (1989b) showed that regression equations can be defined with activity (sitting, standing, walking, cycling), reference insulation and wind speed as variables, without exact knowledge of the clothing ensemble. The regression dealt with total insulation, but for the purpose of this study a separation has been made in intrinsic and air insulation. That separation is possible since the properties of air layers are well investigated.

Air insulation and water vapour resistance
Kerslake (1972) described the convective part of the heat transfer coefficient of air layers around humans by

$$hc = 8.3 \sqrt{v} \tag{18}$$

where v = wind velocity in m/s.

Here, it should be defined what v actually is. In fact there are three wind effects during motion: the effect of motility, the effect of own displacement and the effect of external wind. The latter two will be lumped in one variable, Vwind, expressing the air motion relative to the subject. The former can be expressed as an equivalent air velocity, Vact, depending on the rate of motion, and be added to Vwind. This concept, that has already been proposed by Givoni and Goldman (1972), is redefined here as

$$Veff = Vo + Vwind + Vact \tag{19}$$

where Vo is a lower limit, related to natural convection.

On basis of the measured air insulation by Havenith et al. (1989a) the following expressions are found

Vo = .07 m/s for sitting and .11 m/s for standing
Vact = .67 Vwalk (m/s) for treadmill walking
Vact = .0043 frcyc (m/s) for ergometer cycling

with Vwalk = the walking speed in m/s and frcyc = pedalling frequency in rpm.

The insulation of the surface air layer is then calculated by:

$$Ia = \frac{1}{hr + 8.3 \sqrt{Veff}} \quad (m^2K/W) \tag{20}$$

At the usual temperatures and for typical clothing hr will amount to 4 to 5 W/m^2K.

The air equivalent of the outer air layer is, following equation 6:

$$da = \frac{\lambda}{hc} = \frac{.026}{8.3 \sqrt{Veff}} \quad (m) \tag{21}$$

Intrinsic insulation and water vapour resistance

According to Havenith et al. (1989a,b) the effect of wind on intrinsic insulation is only moderate, while the effect of activity is strong. The interaction between the two justifies the use of multiplicative factors. The factor for wind is deduced from the finding (Fonseca and Breckenridge, 1965; Stuart and Denby, 1983) that wind increases the heat transfer coefficient linearly with the square root of air velocity

$$h = a + b\sqrt{Veff} \tag{22}$$

The ratio of insulation with and without wind is then

$$\frac{Icl\ wind}{Icl\ no\ wind} = \frac{a/b + \sqrt{Vact + Vo}}{a/b + \sqrt{Veff}} \tag{23}$$

bearing in mind that without wind Vact + Vo remains. By experimental fit to the data set of section 3.2 a/b was determined as 3.

Intrinsic insulation is progressively affected by sitting, walking or cycling with increasing activity level and with increasing reference insulation value (standing, no wind). The following regression equations have been found for a number of literature data

$$Icl_{sit} = Icl_{ref}\ (.9 - .6\ Icl_{ref}) \cdot \frac{3 + \sqrt{.07}}{3 + \sqrt{Vwind}} \tag{24}$$

$$Icl_{stand} = Icl_{ref} \cdot \frac{3 + \sqrt{.11}}{3 + \sqrt{Vwind}} \tag{25}$$

$$Icl_{walk} = Icl_{ref} \cdot e^{-\frac{Icl_{ref} \cdot Vwalk}{.45}} \cdot \frac{3 + \sqrt{Vact + .11}}{3 + \sqrt{Veff}} \tag{26}$$

$$Icl_{cyc} = Icl_{ref} \cdot e^{-\frac{Icl_{ref} \cdot fr_{cyc}}{33}} \cdot \frac{3 + \sqrt{Vact + .11}}{3 + \sqrt{Veff}} \tag{27}$$

In equations 26 and 27 the effect of motility is included in the exponential term, together with the effects of bellows ventilation and internal convection, since these effects are not separately known.

The exponential expression in 26 and 27 was introduced to both fit the data and show the correct asymptotic behaviour. Nevertheless the validity domain of the expressions 24 through 27 is restriced to

wind speed	0 to 10 m/s
walking speed	0 to 1.5 m/s
cycling frequency	0 to 100 rpm
reference insulation	0 to .4 m^2K/W

Similar equations can be given for the intrinsic air equivalent dcl, but dcl can be calculated from Icl by recognizing that the convective part of the heat transfer coefficient (hclc) is proportional to the mass transfer coefficient 1/dcl. Actually, hclc is responsible for the variations of Icl with activity and air motion.

In order to calculate dcl, first the convective heat transfer coefficient of the average trapped air layer (htrapc) is solved from:

$$Icl = \frac{nlay}{htrapr + htrapc} + \frac{th}{.042} \tag{28}$$

where nlay = number of clothing layers
th = total thickness of clothing layers (m)
.042 = conductivity of clothing layers (W/mK)

Equation 28 is only approximate since the effect of increasing surface area for the outer layers is neglected. Next, hclc is calculated by the similar equation 29:

$$hclc = 1 \;/\; \left(\frac{nlay}{htrapc} + \frac{th}{.026} \right) \tag{29}$$

where .026 is the conductivity of the air, contained in the clothing layers.

Finally dcl is calculated by:

$$dcl = dcl_{ref} \frac{hclc_{ref}}{hclc} \tag{30}$$

where ref refers to the reference condition (standing in still air).

3 EVALUATION

3.1 Reference insulation and vapour resistance

The model has been programmed in Fortran (Cloman V3.02) and the program was run with the input data (assembly thickness, total thickness of clothing layers, number of clothing and trapped air layers, vapour resistance of non-textile materials, all per segment of the body) from 22 clothing assemblies, that have been evaluated on a thermal manikin by McCullough et al. (1989).

The assemblies cover a wide range of office, casual and work clothing, including a number of coveralls with water vapour hampering coatings. Details are specified in Appendix I. McCullough et al. determined experimentally the values for It, dt, and fcl. From these data Icl and dcl were calculated using the relationships 16 and 17 and the values of Ia = .112 m^2K/W and da = 6.4 mm for their environment.

The experimental data were compared to the model prediction. Fig. 4 shows the correlation for Icl. The standard deviation from the line of identity is .025 m^2K/W. Assembly 2 is an outlier, for as yet unclear reasons. It is a women's business ensemble.

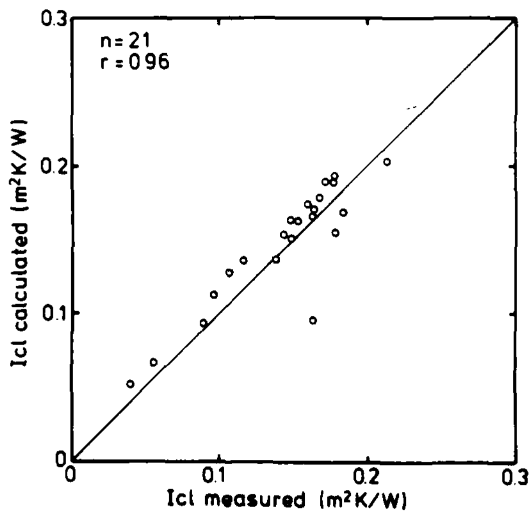


Fig. 4 Correlation between measured and calculated intrinsic insulation using the cylinder model.

In Fig. 5 the calculated surface factor fcl is plotted against the experimentally determined values. For the tight garments (low fcl) there is agreement, but in the voluminous range the calculated values tend to be larger than the measured values. The ratio (fcl - 1)/Icl is about the same for the calculated (1.74 ≈ 27%/clo) and the measured data (1.68 ≈ 26%/clo) and agrees with the literature (Lotens, 1989b).

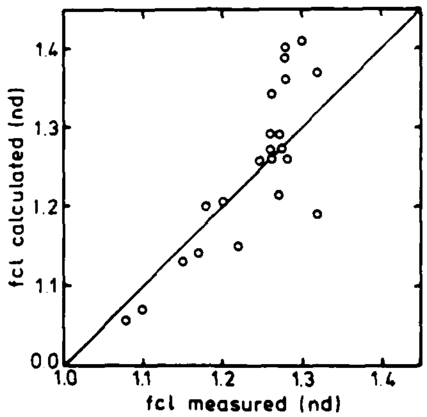


Fig. 5 Correlation between measured and calculated surface area factor using the cylinder model.

In Fig. 6 the relationship is shown between the calculation and measured intrinsic vapour resistance data. Also here there is only a small deviation from the identity line (sd 1.8 mm), with exception of assembly 2 (that also deviated in insulation and fcl) and slightly more for the impermeable garments 21 and 22. The latter have a material vapour resistance of the order of 160 mm, but due to uncovered skin the assembly has a vapour resistance of about 50 mm.

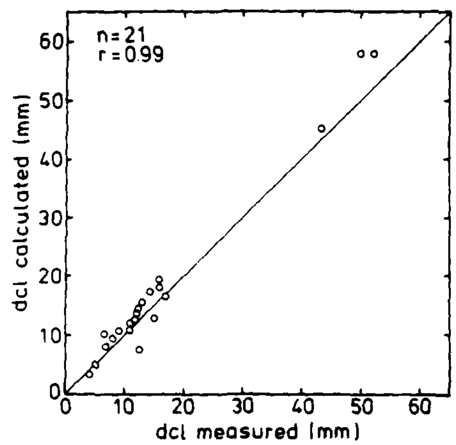


Fig. 6 Correlation between measured and calculated intrinsic water vapour resistance using the cylinder model.

3.2 The effect of activity and wind on insulation

The effect of sitting, walking and cycling at various rates, and wind has been evaluated by simulating the conditions in eight experiments, described in the literature. Each ensemble has been characterized by its reference insulation (i.e. standing in still air) and the percentage covered skin area.

The experiments are briefly described by:

1. (Nielsen et al., 1985). Measurements on subjects, while sitting, standing, cycling at 40 rpm, walking at 1.05 m/s, and walking in wind of 1.1 m/s. Four male's and three female's ensembles varying from semi-nude to heavy workclothing.
2. (Olesen et al., 1982). Measurements on manikin, while sitting, standing, cycling at 40 rpm for the forementioned male's ensembles and also while walking 1.05 m/s with and without wind (1.1 m/s) on one of the ensembles.
3. (Havenith et al., 1989a). Measurements on subjects, while sitting, standing, and walking at .3 and .9 m/s, combined with wind speeds of 0, .7 and 4.1 m/s. Three typical work ensembles, one of which with a windproof coverall.

4. (Havenith and Van Middendorp, 1985). Measurements on subjects while standing, cycling 40 rpm, and standing in wind of 2.5 m/s. Four military clothing ensembles varying from fatigues to intermediate cold weather clothing.
5. (Van de Linde and Lotens, 1982). Measurements on subjects while standing in calm air and in wind (4 m/s). Two rather similar cold weather ensembles.
6. (Lotens et al., 1988). Measurements on subjects, while sitting, standing, standing in wind (3 m/s) and walking 1.1 m/s. Two CW-protective ensembles.
7. (Breckenridge and Goldman, 1974). Measurements on a manikin while standing in various wind speeds up to 4 m/s in tropical fatigues.
8. (Umbach, 1988). Measurements on a standing manikin at wind speeds of .3, 2.5 and 4 m/s. Heavy worksuit ensemble.

For each experimental condition in these experiments the prediction has been compared to the measured insulation value. Fig. 7a shows the results for the total insulation. The standard deviation from the line of identity is .022 m^2K/W for all experiments together. The resulting high correlation between the measured and predicted value of It ($r = .94$) is not a decisive measure for the quality of the prediction since various ensembles are included, that are spread along the line of identity. A better measure is the correlation between calculated and measured changes in insulation, relative to the reference value (Fig. 7b).

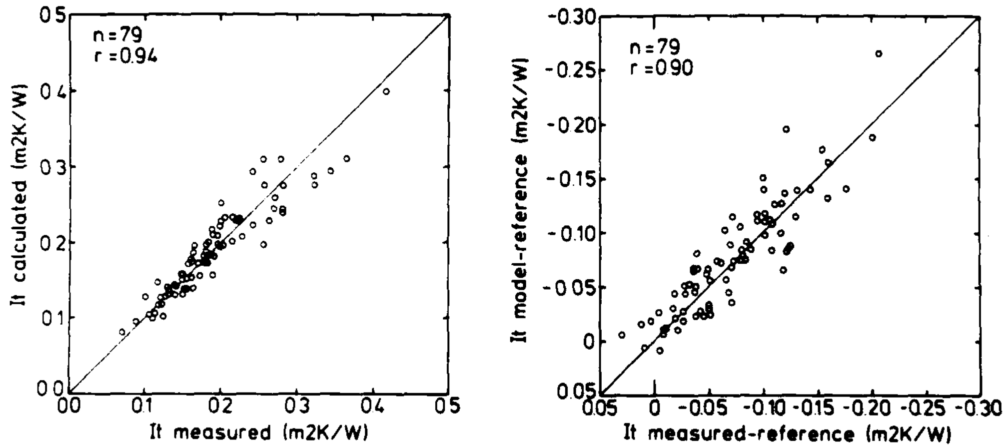


Fig. 7a Correlation between measured and calculated total insulation using the regression equations on activity and wind.
Fig. 7b Correlation between measured and predicted effect of activity and wind, on total insulation relative to the reference condition.

Here indeed is shown that the model adequately describes the effects, since the correlation is .90 and consequently 81 percent of the variance due to activity and wind is explained by the model. The remaining 19 percent is due to imperfections, but also to experimental inaccuracy.

In Fig. 8a and b similar graphs are presented for the intrinsic insulation Icl. The accuracy of Icl is comparable to that of It, with a standard deviation of .025 m^2K/W, but the explained variance by the model for the change in insulation is somewhat lower: 68%.

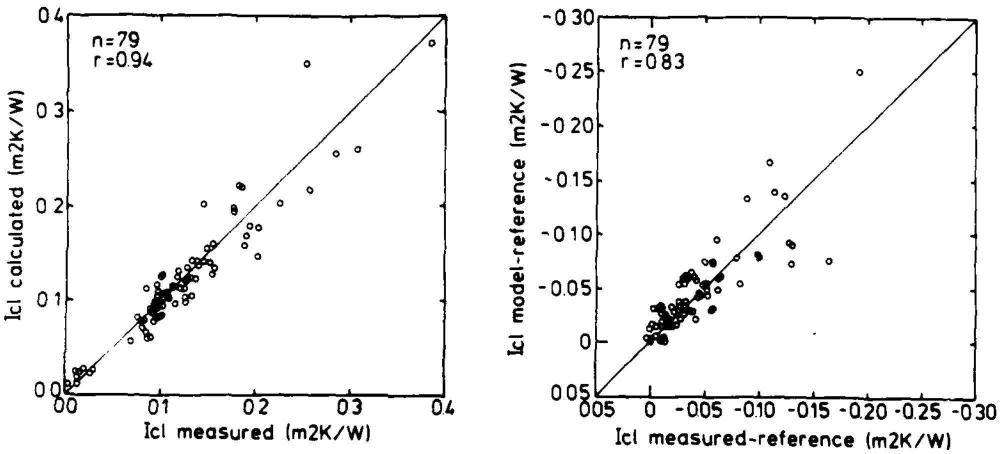


Fig. 8a Correlation between measured and calculated intrinsic insulation using the regression equations on activity and wind.
Fig. 8b Correlation between measured and calculated effect of activity and wind on intrinsic insulation, relative to the reference condition.

Regression analysis shows that there is a significant, but generally small constant term in all variables except Icl. These constants emerge from the differences in still air insulation in the various studies. These have been neglected in this study. "No wind" was interpreted as the .11 m/s air displacement (.07 during sitting) found in the study of Havenith et al. (1989a), in accordance with expectations on natural convection.

3.3 The effect of activity and wind on vapour resistance

Fewer studies are available on vapour resistance then on insulation. The model has been evaluated on five studies:

1. (Havenith et al., 1989b). Measurements with a tracer gas technique (Lotens and Havenith, 1988) on subjects, while sitting, standing, and walking at .3 and .9 m/s, combined with wind speeds of 0, .7 and 4.1 m/s. Two typical work ensembles, one of which with a coverall.

2. (same study). Measurements on a manikin with a wetted liner, while standing at wind speeds of .2, .7, 1.9, and 4.1 m/s. The same ensembles as in study 1, and a rain suit with vents.
3. (Breckenridge and Goldman, 1974). Measurements on a manikin, covered with a wetted body stocking, while standing at wind speeds of .25 to 4 m/s. Tropical fatigues.
4. (Nielsen and Olesen, 1987). Measurements on subjects, while standing and cycling in still air. Heavy work ensemble.
5. (Lotens et al., 1988). Measurements on subjects with tracer gas while standing, standing in wind of 3 m/s, and walking 1.1 m/s. Two chemical protective ensembles.

Model calculations have been based on the reference values for Icl and dcl, percentage covered skin area, number of clothing layers, and total thickness of clothing layers, for each experiment. Since in these studies dt is determined, and not dcl, the value for the input variable dcl was calculated from dt (in the reference condition: standing in still air) assuming a value of 9.4 mm for da.
Fig. 9 shows the results for dt. There is a significant deviation from the line of identity, which is mainly caused by the coverall ensemble in study 1. The standard deviation from the line of identity is 5.2 mm (without the deviating ensemble about 3 mm), and the regression coefficients .88. In Fig. 9b the effect of activity and wind is plotted, relative to the reference condition. 66% of the variance caused by activity and wind (and by experimental inaccuracy) is explained by the model.

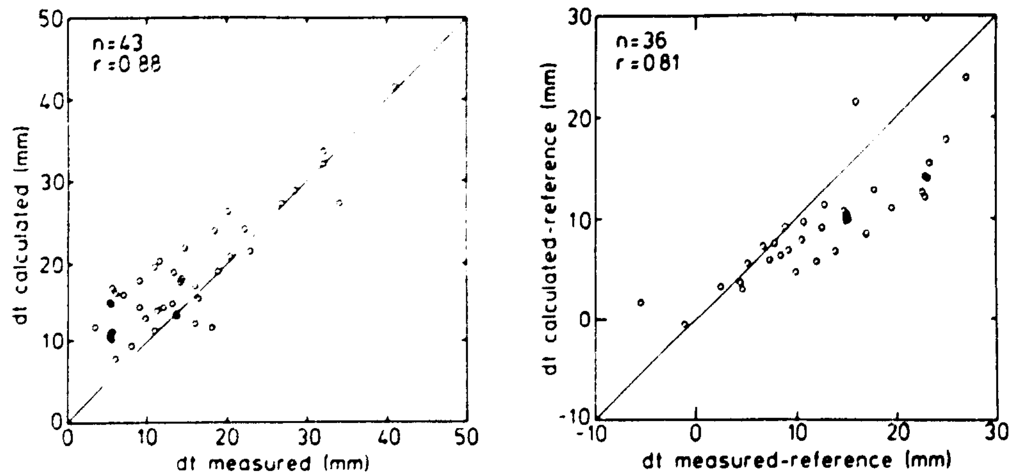


Fig. 9a Correlation between measured and calculated total water vapour resistance, using the regression equations on activity and wind.
Fig. 9b Correlation between measured and calculated effect of activity and wind on total water vapour resistance, relative to the reference condition.

4 DISCUSSION

Accuracy of the model

The first part of the model (predicting reference insulation and vapour resistance) explained 93% of the variance in Icl_{ref} and 99% of the variance in dcl_{ref}. The standard deviation between prediction and measurement was .013 m^2K/W for Icl_{ref} and 3.1 mm for dcl_{ref}. These figures point at a high accuracy of the prediction, since this includes the experimental error that could be expected in manikin measurements, from variation in the arrangement of the clothing. This means that it will be hardly possible to prove alternative models more accurate.

Similar arguments hold for the second part of the model, the effect of posture, motion and wind. The model explains these effects on Icl for 69%, on It for 81% and on dt for 66%, with standard deviations between prediction and measurement of .025 mK/W, .022 m^2K/W, and 5.2 mm, respectively. These figures are not as good as those of the first part, but the reason for this is obvious: the measurements have partly been made on human subjects. Havenith end Heus (1988) reported a stan-

dard deviation for repeated measurements on moving subjects of .011 m^2K/W in Icl, and .017 m^2K/W in It. This is probably a higher error than on manikins. Indeed, the data of Olesen et al. (1982) on a moving manikin fit significantly better than the data on subjects.

McCullough et al. (1989) recently published a model which is quite similar to the first part of the model presented here. Apart from small differences in parameter values used, the difference between the two is that McCullough et al. require the heat and vapour resistance and the geometry of all the layers in the ensemble, whereas this study uses only the geometry of the outer layer and the number of clothing and trapped air layers. Our model assumes that all trapped air layers have equal thickness. Comparison of the predictions on the same set of ensembles shows that the current model is even slightly more accurate. Apparently the detailed (and laborious to obtain) data on the separate layers do not add to the performance of the model.

Intrinsic insulation
The intrinsic insulation, as defined in the usual way, i.e. including nude skin area, is not an invariable clothing characteristic, as the name suggests, but depends on the wind speed (Lotens, 1989b). The reason is the change in relative heat loss through the uncovered areas, when airmotion is altered. In addition to this effect air may penetrate through the clothing and cause a loss of insulation of the covered area as well. Both effects together are lumped in the modifying term $\frac{3 + \sqrt{Vo + Vact}}{3 + \sqrt{Veff}}$ used in equations 2.4 through 2.7.
When the same type of correction is sought for the insulation of the covered skin only, the wind effect is even smaller. In itself it is surprising that the correction is not critical for the type of clothing used. In the experiments garments varied from very light to extreme cold wetter outfit, and all showed satisfactory fit to the prediction. In an earlier paper (Lotens, 1989b) it was concluded that the effect of wind on heavy clothing is less than on light clothing, but the distinction was not so sharp and neglection causes no serious loss of accuracy in the prediction of insulation. This seems to contrast with experiences in chilling conditions, but a windproof jacket that has not been firmly tight up shows considerable ventilation (Lotens and Havenith, 1988) and could thus lead to loss of discrimination from air permeable clothing.
On theory Icl does not only depend on air motion, but on the skin temperature distribution as well. In fact Icl is the result of an averag-

ing of local heat losses. When there is a uniform skin temperature, the heat losses of all body parts are proportional to the temperature difference between skin and air.
When the skin temperature changes, the total heat transfer coefficient (and consequently the insulation) remains the same. This is almost perfectly the case with a warm body but when cold, the skin of the extremities cools deeper than the trunk skin. Therefore the trunk insulation becomes relatively more important for the total heat loss. When insulation is not evenly distributed over the body (usually more on the trunk) this leads to an increased value for Icl.
Icl would loose its meaning then as a clothing constant and calculations should completely be based on heat loss. The use of Icl in heat balance studies should thus be restricted to neutral or warm body conditions.

Surface area factor
The measured surface area factor fcl (Fig. 5) showed an upper limit of about 1.32, whereas the model predictions go beyond that value. The same was found when comparing to the data of Olesen et al. (1982). This could either be due to limitations of the experimental (photographic) method or to the model. There is some evidence for the first hypothesis. Some pairs of ensembles with nearly equal fcl have relevant differences in clothing thickness, and thus in outer surface area. Comparing assemblies 10 and 20, for instance, shows that the latter is thicker by 1.4 cm on the arm, increasing to 3.6 cm on the chest. It must therefore have a considerably larger outer surface, whereas the photographic method reveals equal fcl of about 1.28.
There is a relationship between the intrinsic insulation of clothing, the tightness of fit and the fcl. Loose fitting clothing must have a larger fcl than tight fitting clothing of the same intrinsic insulation. This relation can be characterized by the conductivity λ of all layers together. Burton and Edholm (1955) stated that clothing has a typical insulation of 4 clo/inch, comparing to λ = .042 W/mK. The data in this study suggest that this value is probably correct for fabrics, but that for clothing assemblies λ = .06 would be typical for tight fitting clothing, λ = .10 for normal fit and as high as λ = .15 for loose fit, such as wide coveralls or a robe.
Havenith and Van Middendorp (1985) determined fcl values for various military clothing by simply measuring the exposed clothing surface area and taking the ratio of clothing + bare surface area to skin surface area. The resulting values compare well with those expected

from the model on the basis of λ = .08 and go well beyond fcl = 1.32. It could thus be that this simple method is superior to the more complicated photographic method.

Air insulation

For light garments the total insulation is highly dependent on the air insulation. In the model the air insulation is described as a function of the air velocity (eq. 20). This expression is close to that given earlier by Nelson et al. (1947).

Those experiments in which the clothing surface temperature has been measured, allowing the calculation of air insulation per se, show that this is a fair prediction (Fig. 10).

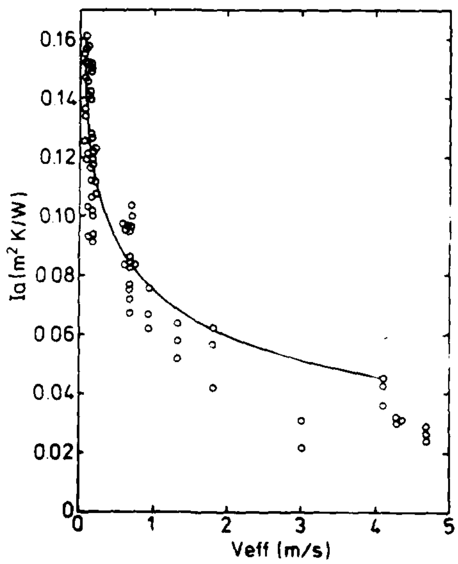


Fig. 10 Measured air insulation as a function of effective wind speed (including motility induced wind). The line represents the prediction.

Some of the experimental values are a bit lower, in particular for the higher wind speeds. This is probably due to experimental errors. Measuring the correct surface temperature in a sharp gradient is difficult and will often result in an underestimation of the gradient,

which in turn leads to an underestimation of the insulation. In fact, expression 20 describes the upper envelope of the measured data, and could well be correct.
Towards low air velocity Ia increases sharply and here a distinction is found between the facilities used in the various studies. Havenith et al. (1989a) find a "still air" insulation of .129 m^2K/W, Nielsen et al. (1985) of .136 m^2K/W, and Olesen et al. (1982) and McCullough et al. (1989) of .112 m^2K/W. This could be the result of slight differences in the direction of the air (vertical or horizontal), turbulence and average air speed. Laminar flow is not stable at air speeds of the order of .1 to .2 m/s, in particular not in the presence of thermal gradients. Consequently the differences in total insulation of light clothing, calculated with the model on the basis of .129 m^2K/W, between the various studies are likely to originate from the lack of definition of the experimental situations.

Vapour resistance
Since there are fewer data available on vapour resistance than on insulation this part of the model is less well confirmed. The most comprehensive data originate from Havenith et al. (1989b), using tracer gas instead of water vapour. Direct comparison with water vapour *diffusion measurements* showed that the tracergas method is reliable but might involve calibration. Havenith et al.'s study shows distinction between the types of garments used. An ensemble with trousers, poloshirt and sweater (A) is correctly predicted by the model, the same ensemble but with a cotton coverall (B) is slightly overestimated. For a third garment (C), including an impermeable coverall, which was discarded from the dataset, there is a dramatic overestimation. It thus seems that the prediction of vapour resistance is more critical with respect to the type of ensemble than the prediction of insulation. When the effect of increasing wind to 4 m/s is observed for the three mentioned ensembles, the vapour resistance (both measured with tracer gas and with water vapour diffusion) drops with a factor of 4 for A, a factor of 5 for B, and a factor of 9 for C. The unexpectedly large drop in vapour resistance of the impermeable garment, compared to that of the heat resistance, is the cause of the misprediction of the model. The reason for the large drop of the impermeable ensemble is that with this type of clothing the internal convection, which enhances heat transfer, has no effect on vapour dissipation. It is the ventilation through the apertures that affects vapour dissipation and apparently the ventilation, though small in magnitude, changes dramatically due to motion and in particular wind. Apparently this type of clothing is outside the validity domain of the model.

A related problem shows with sitting. In particular for coveralls, sitting reduces the insulation and the model interprets this as an increased convection and lower vapour resistance. Measurements rather consistently show that the ventilation drops, however, resulting in higher vapour resistances. Here also the difference in mechanisms for heat and vapour dissipation may produce erroneous results. A further development of this part of the model would be rewarding.

5 CONCLUSIONS

- The cylinder-model for the calculation of heat and vapour resistance of clothing assembles gives a reliable prediction of the reference values, i.e. standing, without wind. Because of the simple measurements involved in the input of the model it is an method that challenges actual manikin measurements.
- Regression equations 24 through 27 predict with reasonable accuracy the change in heat resistance with posture, activity, and wind.
- Analytical deduction of the vapour resistance from the heat resistance is somewhat less accurate. The limitations seem to be related to the relative amount of ventilation through the apertures, such as in impermeable garments during activity or in the wind.

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Remark
The program Cloman V3.02 is available for personal computer.

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

Based on a physical model, in which a human is depicted as a collection of appropriately sized cylinders, clothing insulation and vapour resistance are calculated for standing persons in still air, when the clothing ensemble thickness, total fabric thickness, number of clothing layers, and number of trapped air layers are specified for each cylinder. Specific knowledge of the clothing material is not required, except when coatings of films are involved. The resulting reference values for clothing insulation and vapour resistance are accurate to a standard deviation of .011 m^2K/W and 1.8 mm of air equivalent, respectively, compared to thermal manikin measurements. The reference values are modified for sitting, walking, and cycling at various rates, and for the combined effect with wind. The formulas are regression equations on a data base of literature. The resulting total insulation and vapour resistance are accurate to .022 m^2K/W and 3.6 mm of air equivalent, respectively. The physical model, which is available as software, is a challenge to existing methods for the determination of insulation and vapour resistance with respect to simpleness and accuracy.

16. DESCRIPTORS	IDENTIFIERS
Clothing Thermal Properties Mathematical Model	Heat Transfer Vapour Transfer

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Unlimited availability	-

APPENDIX

Clothing assemblies in KSU-databank.

	measured Icl	measured dcl	model Icl	model dcl
1 Men's business suit	.177	15.2	.155	12.8
2 Women's business suit	.162	12.9	.095	7.4
3 Men's summer casual	.089	6.7	.093	8.0
4 Jeans and shirt	.105	8.9	.129	10.5
5 Summer shorts and shirt	.056	4.7	.066	4.7
6 Women's casual	.095	6.6	.111	9.9
7 Women's shorts and tank top	.040	4.1	.052	3.5
8 Athletic sweat suit	.115	7.8	.134	9.1
9 Sleepwear and robe	.148	11.2	.150	11.8
10 Overalls and shirt	.138	11.0	.137	11.0
11 Insulated coverall and long underwear	.213	16.8	.201	16.9
12 Work shirt and trousers	.141	11.5	.153	12.4
13 Cleanroom coverall +12	.151	12.7	.162	15.4
14 Wool coverall +12	.171	14.1	.189	17.4
15 Firestop cotton coverall +12	.159	12.2	.173	14.4
16 Modacrylic coverall +12	.162	12.2	.166	13.8
17 Tyvek coverall +12	.148	15.4	.164	19.3
18 Goretex 2-piece suit +12	.181	15.1	.167	18.1
19 Nomex coverall +12	.162	12.7	.169	15.8
20 PVC/Poyester acid suit +12	.166	43	.178	44.7
21 PVC/Vinyl acid suit +12	.175	52	.189	58.1
22 Neoprene/nylon suit +12	.177	50	.191	58.3

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